Newer Aspects of Waste Treatment

NANDOR PORGES[1]

Eastern Regional Research Laboratory,[2] Philadelphia, Pennsylvania

I. Introduction

Waste treatment is a means of maintaining or recovering man's most precious and most abused natural resource, fresh water. Fresh water supplies were all-important in the establishment and growth of civilizations. Much of man's bitterest fighting has been incited by altercations over water rights, and the course of history may well be written around the theme of primitive and modern man's need for water.

[1] Dr. Nandor Porges, until his sudden death in April 1959, headed the U. S. Department of Agriculture's research on dairy wastes at the Eastern Utilization Research and Development Division of the Agricultural Research Service, in Philadelphia, Pennsylvania. A native of Hungary, Dr. Porges was a graduate of the University of Massachusetts, and received his master of science and doctor of philosophy degrees at Rutgers University. He is best known for his work in developing a simple, inexpensive process for the disposal of dairy wastes. For this achievement the Department of Agriculture honored his unit with its Superior Service Award. Other honors bestowed on Dr. Porges include the Chilean Nitrate of Soda Fellowships 1927–1929, Sigma Xi honor for research 1931, and membership in Phi Tau Sigma the honor society of food science 1936.

[2] Eastern Utilization Research and Development Division, Agricultural Research Service, U. S. Department of Agriculture.

Dependence on rivers and streams increased as civilization progressed. Waterways became extremely important as sources of potable water as well as highways for travel. Streams became the center of domestic activities such as bathing, washing, animal watering, and waste disposal. Quite naturally, then, the abuse of this resource with disregard to fellowman began early in history. As stream pollution led to the spread of disease, the necessity of water purification and of sewage treatment began to be realized.

Modern industrialized and concentrated centers of civilization require enormous quantities of water and produce prodigious amounts of waste water. Intelligent maintenance of this water supply is a duty and a necessity. In this respect, man has been criminal against himself. Indeed, as science and industry grew, so did neglect and defilement of this essential commodity. Only recently, late in the history of our industrial expansion, has attention been turned to the conservation of water as a natural resource. In many cases, however, legislation and the threat of fines have been necessary to force correction of conditions contributing to stream pollution.

II. Aftermath of Dumping Waste into a Body of Water

The most disastrous and immediate consequence of dumping wastes into a stream is the threat to public health. Communities located down stream from where raw sewage and wastes enter are menaced by possible outbreaks of water-borne diseases that could reach epidemic proportions.

The health of the stream itself, as indicated by its aquatic life, is also affected by indiscriminate waste practices. Biologically speaking, a normal stream supports a teeming population of microorganisms, plants and animals dependent upon each other for food and upon the stream for oxygen. An adequate, dissolved oxygen content is usually maintained by natural physical reaeration of the surface waters. Under normal conditions, this process is able to replace all the oxygen lost to microbial respiration. When an extra load of organic impurities such as sewage and industrial wastes stimulates microbial growth, the supply of dissolved oxygen is quickly exhausted and cannot be replaced rapidly enough. Every stream is thus limited in its capacity to assimilate organic wastes. In many cases, organic pollution leads to a temporarily imbalanced stream condition within a localized area, with eventual recovery effected by natural reaeration. In extreme cases, recovery does not take place, vegetation and fish are destroyed, and the polluted stream becomes an open sewer with its concomitant stenches and disagreeable appearance spoiling the economic and esthetic value of the stream and its environs.

The detrimental effect of industrial organic pollutants on a body of water can be illustrated by examining the effects of the waste waters of a small iry. An average daily waste load may contain the equivalent of 100 pounds of dried skim milk, a well-balanced food readily utilized by microorganisms. Complete combustion of this amount of milk requires about 105 pounds of oxygen. The quantity of aerated water necessary to satisfy this ultimate oxygen demand depends upon the temperature of the water. At 25° C., 8.4 parts of oxygen are dissolved in a million parts of water; hence, 12.5 million pounds of water, or practically 1.5 million gallons, will contain 105 pounds of oxygen. This relatively small amount of organic matter would require all the oxygen in a circular pond 6 feet deep with a diameter of 206 feet, or a pond of the same depth, 100 feet wide and 334 feet long. When sufficient oxygen is not available, disagreeable anaerobic conditions set in and lead to gross pollution harmful to life associated with clean streams.

III. A Glance at Waste-Treatment Procedures

Details of waste treatment are available in specific texts such as "Sewage Treatment" (Imhoff and Fair, 1947), "Stream Sanitation" (Phelps, 1944), "Industrial Wastes" (Rudolfs, 1953), "Bio-Oxidation of Organic Wastes; Theory and Design" (Eckenfelder and O'Connor, 1958), and others. There are also excellent reviews of literature published yearly on sewage, waste treatment, and water pollution by the Federation of Sewage and Industrial Wastes Association Committee on Research in *Sewage and Industrial Wastes* (R. E. Fuhrman, ed.), now in its thirty-first volume. Since many of us in the field of applied microbiology do not have the need or inclination to make a detailed study, a brief glance at waste treatment follows.

Offensive and potentially dangerous wastes are transported from household and industry by the simple and economical water-carriage system. The next step, the removal of these wastes from the water before passing into natural waterways, is accomplished in sewage-treatment plants (Imhoff and Fair, 1947). Strange as it seems, this dirty-looking water that may contain color, and suspended and soluble material, is usually over 99.9% pure water. Very few wastes entering treatment plants exceed solids concentrations of 1,000 mg. per liter, or 0.1%. Removal or stabilization of the waste is done by various methods or combinations of methods but depends mostly on the aerobic and anaerobic activity of microorganisms.

The principles, applications, and design of aerobic oxidation are discussed in a bound series of 33 contributed papers (McCabe and Eckenfelder, 1956). A similar volume of 28 papers covers anaerobic digestion and solids-liquid separation (McCabe and Eckenfelder, 1958). As the carriage-water and its load enters the treatment plant, the floating matter and coarse suspended material are removed by racks and screens. After being shredded and ground, the comminuted matter may be returned to the flowing sewage which passes through a grit chamber, if necessary, to allow sand, grit, and heavy mineral solids to settle. Otherwise, the collected material is buried, incinerated, or digested.

The sewage or carriage-water with its load of finely suspended and soluble matter enters a primary settling tank and is detained for a short while to permit sedimentation of settleable solids. The settled solids are pumped to a sludge-digestion chamber to undergo anaerobic or aerobic digestion. The residue is filtered, dried, and incinerated, or used otherwise. Conversely, the entire sewage may be treated anaerobically.

The carriage-water leaving the primary sedimentation basin usually undergoes aerobic biological treatment for stabilization of the organic matter still in suspension and in solution. This is done in various ways. If there is a limited quantity, it can undergo land treatment by irrigation or by filtration through sandy soil. Aerobic conditions are maintained by intermittent filling and emptying. Another means of removal and stabilization is by passing the liquid through filters consisting of stone or other material. The slimes of living microorganisms covering the contact material remove the organic matter as the liquid trickles through the bed. Aerobic conditions are maintained by passing air through the bed or by intermittent flow of the liquid.

A method extensively used for stabilization is the activated-sludge process in which a sludge floc is maintained in suspension by air diffused into a flowing mixture of sewage and floc. Mechanical agitation may also be used. Activated sludge is the accumulation of floc produced by the growth of zoogleal bacteria and other organisms in the presence of dissolved oxygen. Removal of soluble and suspended matter is achieved by the living mass of microorganisms maintained under aerobic conditions.

The sludge floc which has oxidized or removed the waste material is removed from the carriage-water in a secondary settling tank where the stabilized sludge settles. Various engineering designs are in use to assure settling and thickening of the sludge. A calculated amount of the settled sludge is returned to the aeration tank for re-use. The remaining or excess sludge is mixed with the solids from the primary settling tank and pumped to the digestion tank.

The carriage-water, now free of its load, leaves the final settling tank as a clear liquid. It may be chlorinated before passing into the receiving stream. An extra step may be desirable in which the clear treated effluent is aerated again to reduce the demand on the oxygen of the stream.

The excess sludge, consisting primarily of microbial cells, is conditioned further by anaerobic or aerobic digestion. (In some cases, digestion is replaced by drying and spreading on soil, by hauling to sea, or by disposal in some other manner.) During digestion, the tank contents are kept at

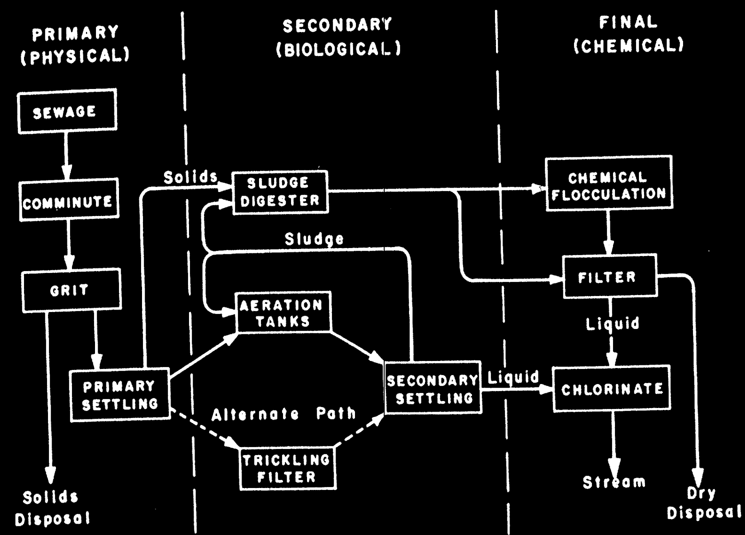

FIG. 1. Major steps in sewage treatment.

a favorable temperature. Methane gas formed in the digestion process is often burned to supply heat for this purpose. The solids are reduced and the dewatering characteristics of the sludge greatly improved by this step, sometimes by the addition of chemicals. The digested sludge is removed from the water by filtration. After this dewatering, the sludge may be air- or heat-dried and prepared for use as a fertilizer, or it may be incinerated. The separated liquid is returned through the process with the entering sewage.

Thus, treatment may be completely aerobic or completely anaerobic but usually consists of a combination of both types plus intricate mechanical and engineering features. Each treatment plant is tailored for its specific service according to the plans of the sanitary engineer, who should be cognizant of the biological processes involved. The flow diagram of Fig. 1 is a composite of essentials of the process, showing the primary or mechanical treatment, the secondary or biological treatment, and the tertiary or chemical treatment. The goal of treatment is a clear effluent, low in offensive solids and in oxygen demand and harmless to aquatic life.

IV. Problem of Concentrated Industrial Wastes

The more or less elaborate processes touched upon in the previous section on waste-treatment procedures work well with simple municipal wastes that are predominantly of household origin or with wastes of similar strength. Such wastes are further diluted by the carriage-water so that they enter the treatment plant with low concentrations of organic matter. The average strength of a municipal waste may be about 180 parts per million, or 180 mg. per liter of 5-day B.O.D. (The B.O.D. is the biochemical oxygen demand, or the quantity of oxygen utilized by the microorganisms in the biochemical oxidation of the organic matter in the waste, as determined under standard conditions at 20° C. The 5-day B.O.D. is the oxygen utilized in 5 days' incubation. The ultimate oxygen demand is usually considered as the 20-day B.O.D. and in a few wastes such as dairy wastes may be approximated by the C.O.D., or chemical oxygen demand, as determined by various methods of chromate oxidation. The 5-day B.O.D. has been generally accepted as 68.5% of the 20-day B.O.D. for sewage (Phelps, 1944), although this may vary. Thus, 1.46 times the 5-day B.O.D. will approximate the ultimate oxygen demand, but specific values should be determined for each waste.)

It has been calculated that the average amount of 5-day B.O.D. contributed per capita per day is 0.167 pound or about 75 to 76 gm. (Imhoff and Fair, 1947). The ultimate oxygen demand per capita is then about 0.244 pound or 110 gm. It is possible to determine "population equivalents" of any industrial or concentrated waste. The amount of organic matter to be treated may also be estimated from the C.O.D. if it is realized that the C.O.D. varies with the organic substance. Thus, a unit weight of sugar has a C.O.D. of 1.07 and a unit weight of protein, a C.O.D. of 1.44 (Porges *et al.*, 1950). From the average of these values, the 110 gm. of C.O.D. is equivalent to 88 gm. of dry organic matter. When this is diluted in 419 liters of water, the concentration will be 180 mg. per liter of 5-day B.O.D. More often, the waste is more dilute, allowing treatment to be accomplished easily and yielding clear effluents low in oxygen demand that may be discharged into a receiving stream.

As industries grew, the wastes received by many municipalities did not respond to treatment, and the plants were unable to cope with the extra load. Collections of data on sources of pollution have been made, and strengths of many industrial wastes were calculated in terms of their population equivalents (U. S. Public Health Service, 1944; Phelps, 1944). In many communities the industrial wastes impose a greater pollution load than that of the population itself. Selected values are shown in Table I. The daily population equivalent of the more important oxygen-demanding wastes of this country was estimated to be 134,300,000 in 1949. This does not include the added load supplied by small industries such as dairies and laundries (Rudolfs, 1953). Not only is the population equivalent of industrial wastes greater than that of municipal wastes, but the actual concentration is greater. Dairies average about 1,200 mg. per liter B.O.D.,

TABLE I
POLLUTING EFFECT OF INDUSTRIAL WASTES

Population equivalents	Source of waste	Amount handled or made
8	Dairy plant	100 lb. of milk
14	Brewery	Barrel of beer
21	Abattoir	One animal
24	Laundry	100 lb. of clothes
1,690	Straw board	Ton of paper
4,600	Sulfite pulp	Ton of paper

canneries have slightly less, but wastes from antibiotic-producing plants may exceed 13,000 mg. per liter B.O.D.

We can imagine the difficulties that sewage plant operators have when a treatment plant designed to handle wastes with a concentration of 200 mg. per liter B.O.D. suddenly receives a large volume of industrial waste with a B.O.D. of 1,000 mg. per liter. The plant becomes overloaded, incoming sewage is not treated properly, odors develop, the carriage-water is not purified, and a breakdown of the whole process may occur. Reestablishment of the proper activities in the aeration tanks may require weeks and may be almost impossible if strong wastes continue to be received.

V. Laboratory Approach to Problem

Lack of understanding of the biochemistry and microbiology involved in the stabilization of the suspended and soluble waste often leads to difficulties in waste treatment. Treatment plants were often constructed on empirical information that disregarded the effect of waste concentration and toxicity of influents. Aerobic treatment of waste waters has been practiced for about a half a century. Fortunately, domestic waste is a well-balanced biological mixture, and little or no difficulty was encountered in its treatment. The increase in volume and types of industrial wastes, treated with municipal wastes or separately, called for an application of knowledge concerning the biochemistry of treatment.

The action of microorganisms is primarily responsible for the purification of the carriage-water. Rapid purification depends on the unrestricted activities and reproduction of these organisms. The best growth and purification occur when the organic waste is nutritionally balanced. Extensive studies have been made on this phase by various workers and have been reviewed (Sawyer, 1956). The importance of oxygen has been stressed and detailed (Eckenfelder and Weston, 1956; Porges *et al.*, 1953).

Waste treatment involves the handling of relatively large quantities of dilute material. The microorganisms are usually present in higher concentrations than the waste itself. Sludge concentrations in an aeration chamber may be about 2,000 mg. per liter, while that of the organic matter may be only 200 mg. per liter.

In this discussion, the importance of selected laboratory studies in devising successful treatment of various wastes is emphasized. The biochemical oxidation of this waste is a study of the problem of propagation of microorganisms in a dilute solution. Laboratory data obtained on dairy wastes (Porges, 1956, 1958a, b) were translated to studies for a pilot plant treating 10,000 gallons of waste daily (Kountz, 1953). The results are being applied in developing satisfactory designs for the aerobic treatment of various industrial wastes (Kountz, 1954; Eckenfelder and O'Connor, 1958).

VI. Nutrient Requirements

Stabilization of a liquid waste entails the conversion of the soluble material to a removable insoluble substance, gas, and water, and depends upon the nutrition and growth of microorganisms that have the ability to gather the food supply and minerals to produce new generations of cells. Carbon, nitrogen, and phosphorus are required and occur in most wastes. The general change involving the use of the organic matter for cell synthesis and for energy may be shown as:

$$\text{Organic waste} + \text{oxygen} + \text{bacteria} \rightarrow \text{more bacteria} + CO_2 + H_2O \qquad (1)$$

The deficiency of nitrogen and of phosphorus in many industrial wastes such as those obtained from cotton, rope-making and paper-making plants, breweries, and other factories, required supplementation with these elements (Sawyer, 1956). Wastes from slaughter houses and tanneries contain nitrogen in excess of that required for stabilization by activated sludge. In such cases, other problems may arise due to nitrification, which may prevent sludge from settling and interfere with its removal.

The carbon to nitrogen ratio and the carbon to phosphorus ratio become of importance. Waste treatment workers express this as the 5-day B.O.D. to N ratio. The relationship between carbon, C.O.D., and 5-day B.O.D. is 12, 32, and 21.9 for ordinary wastes. When necessary, available nitrogen may be supplied from inorganic sources, or domestic sewage may be admixed with the industrial waste. The sludge itself may serve as a nitrogen source under certain conditions (Porges *et al.*, 1955).

Various studies showed that a B.O.D. to N ratio of 17 to 1 was optimum for stabilization of low nitrogen wastes in the presence of sewage (Helmers *et al.*, 1952). In terms of ultimate or chemical oxygen demand, the C.O.D.

N ratio calculates to be about 25 to 1. Since the oxygen demand is a measure of the carbon oxidized, and one molecule of carbon combines with one molecule of oxygen, the carbon to nitrogen ratio becomes 9.4 to 1. Only that nitrogen available to the microorganisms is considered and may be present as the ammonium ion from salts, urea, or products of hydrolysis. The availability of nitrogen from various organic sources ranges from 30 to 70% (Burk and Horner, 1939). A recent report claims that nitrates are also readily used (Symons and McKinney, 1958). Stabilization may be accomplished with less nitrogen, but longer periods of time may be needed, with a wide B.O.D. to N ratio of 32 to 1, equal to a C to N ratio of 17.5 to 1 (Sawyer, 1956). On the other hand, the critical phosphorus levels are much lower, with the B.O.D. to phosphorus ratio varying from 90 to 1 up to 150 to 1, showing that one unit of P is required for 49 to 82 units of C.

Even though the change seems to be simple, the treatment of a well-balanced material such as skim milk or dairy waste can cause trouble. Intensive laboratory studies on dairy wastes were made which led to the proposing of certain principles of biological oxidation (Porges *et al.*, 1956) which will be discussed.

VII. Preliminary Laboratory Studies on Treatment of Dairy Wastes

The necessity of removing the oxygen demand of dairy waste led to a laboratory study of its aerobic treatment (Porges *et al.*, 1950), since failures of many existing aeration systems to prevent odor or acid formation were apparently caused by an insufficiency of oxygen. Laboratory tests were made in a fermentor holding 20 liters of liquid under excess aeration. A solution of one gram of dried skim milk per liter contained 369 mg. of protein, 505 mg. of lactose, 9 mg. of fat, and 81 mg. of ash. This waste, then, contained 883 mg. of organic solids out of a total of 964 mg. of solids. Assimilation occurred so rapidly that changes were measured by a specially adapted chromate oxidation procedure. The C.O.D. was about 1,050 mg. per liter. The 5-day B.O.D. calculated from this was 715 mg. per liter and compared to a value of 636 found by actual test.

The C.O.D. test proved indispensable in the laboratory investigations. The C.O.D. of 1,000 mg. of the organic matter of the milk was 1,200 mg.; of the same weight of lactose anhydride, 1,123 mg.; and of lactose hydrate, 1,066 mg. By analysis, milk protein (casein) had a value averaging 1,440 mg. Likewise, 1,000 mg. of aerated sludge cells averaged 1,250 mg. of C.O.D. These factors were of value in subsequent work.

A solids balance was made on the influent and on the mixed effluent of a continuous aeration experiment (Hoover and Porges, 1949). Of 35 units of protein and 53 units of carbohydrate in the influent waste, 34 units of protein and 27 units of carbohydrate were found in the removable cells of the mixed effluent. A unit of protein and 2 units of carbohydrate still remained in solution. A total of 44 units of organic matter had been oxidized to carbon dioxide and water. These results agreed with those of other workers (Placak and Ruchhoft, 1947). Assimilation of available waste into cellular substance is of primary importance in the growth process. About half of the available organic material was oxidized, while half was converted to cell substances.

Manometric investigations on the assimilation of dairy waste by activated sludge (Hoover *et al.*, 1951b) showed that each component of the milk was readily available to the mixed bacterial population. Failures in treatment of dairy waste could not be attributed to the inassimilability of its individual components. Respirometer techniques (Umbreit *et al.*, 1957) were used for this study, as it had been reported that carbon dioxide was the only gas evolved in the early periods of aerating an activated sludge (Caldwell and Langelier, 1948; Dawson and Jenkins, 1949).

Several experiments showed that 0.5 mg. of well-aerated sludge cells in phosphate buffer removed 1 mg. of skim milk, 0.5 mg. of lactose, or 0.35 mg. of casein from the substrate in the presence of excess ammonium sulfate. Within 6 hours, the high rate of oxidation in these vessels dropped to the slow rate of unfed controls. Lactose and casein were oxidized at the same rate and to about the same degree, as measured by carbon dioxide evolution.

VIII. Oxygen Requirements

Oxygen requirements for stabilization or conversion to cell substance of any organic substance may be determined. We shall use the results obtained with skim milk and its ingredients to demonstrate the application of this information.

One mole of lactose hydrate requires 12 moles of oxygen for complete combustion:

$$C_{12}H_{22}O_{11} \cdot H_2O + 12\ O_2 \rightarrow 12\ CO_2 + 12\ H_2O \qquad (2)$$

Therefore, each gram of lactose requires 1.06 gm. of oxygen. In the respirometer studies plotted in Fig. 2, the lactose added should have required 1110 μl., but only 465 μl., or 42% of the theoretical amount, was used during the 6-hour experiment (Hoover *et al.*, 1951b).

Likewise, the oxygen required for the complete combustion of this sample of casein was calculated from its chemical analysis, which was carbon 53%, hydrogen 7.0%, nitrogen 15.7%, and oxygen 27.7%. Other elements such as sulfur and phosphorus were not considered because of their presence in low amounts. Assuming that nitrogen is converted to ammonia and the oxygen to water, the oxygen requirement of 1 gm. of this casein (8% moisture), calculated from its carbon content, was 1.41 mg. The casein used in the Warburg vessel should have required 1000 μl. of oxygen for complete combustion. The actual amount of oxygen used was 420 μl. or 42% of the total required.

The oxygen equivalent of the skim milk may be determined from the oxygen requirements of its components. This milk sample contained 36.3% protein and 50% lactose. The total oxygen requirements per gram of skim milk are, then, $(363 \times 1.41) + (50 \times 1.06)$, or 1,042 mg. The sample used should have required 2340 μl. of oxygen, but only 864 μl., or 37% were used.

The values would indicate that partial oxidation or assimilation occurred. Other experiments showed that little or no oxidizable material was left in solution; therefore the remaining 58 to 63% of oxygen demand was assimilated by the sludge cells. Figure 2 shows that the casein and lactose are oxidized at the same rate and to the same extent by the conglomerate of organisms. The respiratory quotients of 1.00 to 1.03 of these systems tended to confirm the idea that the substrate is completely assimilated or oxidized.

Respirometer studies can also be of value to plant operators. In addition to showing the rate and extent of oxidation, the ability of a sludge to oxidize specific wastes can be determined rapidly, the requirements for nutrient supplementation may be ascertained, and the effect of other environmental conditions, such as pH or toxic substance, may be measured. Since manometric equipment and techniques are not generally available, a method in which carbon dioxide production is measured may be used to

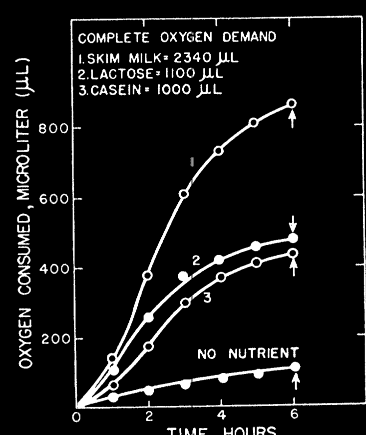

FIG. 2. Oxygen requirements for stabilization of skim milk, lactose, and casein, determined manometrically.

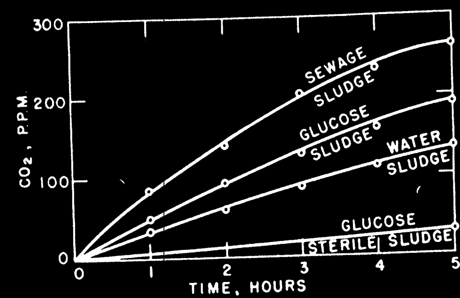

FIG. 3. Carbon dioxide revolution from sludge mixtures.

determine sludge microbial activity (Porges *et al.,* 1952). It has already been shown that, with dairy waste, the carbon dioxide evolved was equal to the oxygen consumed (Dawson and Jenkins, 1949). A known volume of mixed liquor is aerated with carbon dioxide-free air, and the spent air is passed through a solution of barium hydroxide (Fred and Waksman, 1928) or sodium hydroxide (Association of Official Agricultural Chemists, 1955) to trap the carbon dioxide, which is determined volumetrically. The quantities of carbon dioxide evolved, as determined by oxalic acid titration of barium hydroxide, when glucose and sewage were added to sludge, are shown in Fig. 3. The changes were followed by hourly analyses.

IX. Assimilation and Synthesis

The various experiments emphasized the fact that the removal of polluting organic substances by bio-oxidation depends upon the assimilation of part of the organic substances by the microorganisms present in the mixed waste-sludge liquor, while part is completely oxidized. If this is so, then the general equation [see Eq. (1)], expressing the conversion of soluble wastes, may be amplified to express a stoichiometric relationship for each waste or for each ingredient of the waste. In order to obtain such a relationship, the composition of the sludge cells must also be known. Armed with this information concerning the waste, the cells, and the oxygen requirements, we can give more detailed consideration to the system.

A chemical determination of the sludge cells was obtained to establish an empirical composition of the organisms (Table II). The per cent composition of the elements was converted to a molar basis by dividing the analytical value by the proper atomic weight. The results were converted, using the lowest value for unity, in this case, nitrogen, and then rounded off to the nearest whole numbers. A close approximation of the resultant composition is $C_5H_7NO_2$, omitting P and S (Hoover and Porges, 1952). It is realized that such an oversimplification does not take cognizance of the infinite complexity of the organized cell system. This empirical formula

TABLE II

ANALYSIS AND EMPIRICAL COMPOSITION OF SLUDGE CELLS

Constituents	Atomic weight	Weight (%)	% Wt./atomic wt.	Ratio of atoms	Atoms in cell
C	12	47.26	3.94	4.86	5
H	1	5.69	5.69	7.02	7
N	14	11.27	0.81	1.00	1
O	16	27.00	1.69	2.09	2
Ash	—	8.61	—	—	—

expresses only a statistical average proportion of the major atoms of the organic constituents. Thus, the $C_5H_7NO_2$ sludge has a "mole weight" of 113 or, if the ash is taken into consideration, 124. Variations from this composition may be expected but are not significant for practical purposes and will approximate basic constituents of the cells.

Lactose of the waste is converted to cell material and energy through bio-oxidation. Since by-products are not produced, the energy-yielding step must be the complete oxidation to carbon dioxide and water:

$$C_{12}H_{22}O_{11} \cdot H_2O + 12\ O_2 \rightarrow 12\ CO_2 + 12\ H_2O \tag{3}$$

or, for convenience, we can express this in terms of the monomeric unit:

$$(CH_2O) + O_2 \rightarrow CO_2 + H_2O \tag{4}$$

In order to produce cell substance from lactose and ammonia, the minimum equation is:

$$5(CH_2O) + NH_3 \rightarrow C_5H_7NO_2\ (+\ 3\ H_2O) \tag{5}$$

Oxygen consumption and carbon dioxide evolution have not been taken into consideration in Eq. (5). Since an average of only 37.5% of the theoretical total oxygen requirements was used during assimilation, 37.5% of the available carbon was oxidized. Thus, 3 carbons are oxidized, while 5 carbons are changed to cells:

$$8(CH_2O) + 3\ O_2 + NH_3 \rightarrow C_5H_7NO_2 + 3\ CO_2 + 6\ H_2O \tag{6}$$

This satisfies the analytical data, has a respiration quotient of unity in that the oxygen used equals the carbon dioxide evolved, and has no side reactions. The yields are also consistent with experimental data. Equation (6) shows that the yield of organic matter will be 47% of the weight of lactose used, or 52% if the cell ash is included. These values are approximated by the 50% yield obtained experimentally.

Similarly, if the composition of casein is known, equations for its oxidation and assimilation may be developed. A sample was analyzed, with the

TABLE III

Analysis and Empirical Composition of Casein

Constituent	Atomic weight	Weight (%)	% Wt./atomic wt.	Ratio of atoms	Atoms in casein
C	12	52.85	4.40	8.14	8
H	1	6.48	6.48	11.99	12
N	14	15.12	1.08	2.00	2
O	16	24.76	1.55	2.87	3

results shown in Table III, to give an empirical formula of $C_8H_{12}NO_2$ for casein. Sulfur and phosphorus have been omitted, as they are present in fractional parts of a percent.

Complete oxidation of this casein must occur thus:

$$C_8H_{12}N_2O_3 + 8\ O_2 \rightarrow 8\ CO_2 + 2\ NH_3 + 3\ H_2O \qquad (7)$$

The requirements imposed by the results of the respirometer studies showing that 37.5% of the carbon is oxidized, are met by the following equation:

$$C_8H_{12}N_2O_3 + 3\ O_2 \rightarrow C_5H_7NO_2 + NH_3 + 3\ CO_2 + H_2O \qquad (8)$$

Quantitative determinations for ammonia were not made, but qualitative evidence showed its release when sludge cells were grown on casein alone. When 20 liters of mixture were vigorously aerated and agitated, the odor of ammonia was strong, and there was a rise in the pH of the solution.

Fortunately for our studies on dairy wastes, the proportion of lactose and of casein found in the synthetic skim milk waste were the same as that required to produce a mole of cell substance.

Then, by adding Eqs. (6) and (8):

$$8(CH_2O) + 3\ O_2 + NH_3 \rightarrow C_5H_7NO_2 + 3\ CO_2 + 6\ H_2O \qquad (6)$$

$$C_8H_{12}N_2O_3 + 3\ O_2 \rightarrow C_5H_7NO_2 + NH_3 + 3\ CO_2 + H_2O \qquad (8)$$

we get:

$$8(CH_2O) + C_8H_{12}N_2O_3 + 6\ O_2 \rightarrow 2\ C_5H_7NO_2 + 6\ CO_2 + 7\ H_2O \qquad (9)$$

Again conditions have been satisfied, and a 53% yield of sludge organic matter may be expected, based on the weight of skim milk organic matter added.

X. Endogenous Respiration

The unfed sludge cells also have an oxygen demand, although they require much less than those grown in the presence of soluble nutrients (Fig.

2). This lower oxygen demand is due to endogenous respiration, during which oxidation of the sludge constituents occurs thusly:

$$C_5H_7NO_2 + 5\ O_2 \rightarrow 5\ CO_2 + NH_3 + 2\ H_2O \tag{10}$$

The latter occurs at a slow rate of oxygen consumption of about 8 to 12 ml. per gram of sludge cells per hour (Hoover *et al.*, 1952b). The rate of endogenous respiration tends to decrease with the age of the cells, and in the course of that experiment a Q_{O_2} of 10 was the average hourly rate. The Q_{O_2} of various microorganisms reported in literature ranges from 4 to 25 at 22°C., with an average value of 10 (Hoover *et al.*, 1953).

The major reactions for these material balance equations for organic-matter oxidation, cell-material synthesis, and cell-material oxidation have been generalized (Weston and Eckenfelder, 1955).

Organic matter oxidation:

$$C_xH_yO_z + \left(x + \frac{y}{4} - \frac{z}{2}\right) O_2 \xrightarrow{\text{enzyme}} xCO_2 + \frac{y}{2} H_2O - \Delta H \tag{11}$$

Cell material synthesis:

$$n(C_xH_yO_z) + nNH_3 + n\left(x + \frac{y}{4} - \frac{z}{2} - 5\right) O_2 \xrightarrow{\text{enzyme}} (C_5H_7NO_2)_n + n(x - 5)CO_2 + \frac{n}{2}(y - 4)H_2O \pm \Delta H \tag{12}$$

Cell material oxidation:

$$(C_5H_7NO_2)_n + 5nO_2 \xrightarrow{\text{enzyme}} 5n\ CO_2 + 2n\ H_2O + n\ NH_3 - \Delta H \tag{13}$$

In Eqs. (11), (12), and (13), x, y, and z may be positive or zero, according to the compound found in the waste. The heat of reaction is represented by ΔH and may be endothermic, isothermic, or exothermic. Energy must be supplied from Eq. (11) if Eq. (12) is endothermic or isothermic. If the organic compounds contain sulfur or nitrogen, the general equations must be modified.

Eqs. (10) and (13) show that self-digestion or sludge burn-up requires 160 weight units of oxygen to completely oxidize 113 weight units of cell organic matter. Thus, one gram of cell material is equivalent to 1.42 gm. of oxygen, which has a volume of 1,000 ml. Since the Q_{O_2} is the microliters of oxygen used per milligram of cells per hour, a Q_{O_2} of 10 as found for endogenous respiration is 14.2 μg. of oxygen used per milligram of cells per hour. Equation (10) shows this amount of oxygen represents 14.2 × 113/160, or 10 μg., of oxidized cell material. Since this weight is one-hundredth of a milligram, a Q_{O_2} of 10 shows the oxidation of 1% of the cells per hour for the period of the study, a Q_{O_2} of 5 represents 0.5% burn-up, and so on.

It should be theoretically possible to arrange conditions so as to maintain a balanced system in which sludge or cells do not accumulate. All that would be required is sufficient nutrients to produce enough cells to replace those being oxidized by endogenous respiration. For example, if 1,000 gm. of skim milk are added to an aeration chamber per day, about 500 gm. of sludge are produced. If the Q_{O_2} of the unfed sludge is 10, about 20% of its own weight would be oxidized per day. Therefore, to maintain a balance, the 500 gm. of new cells must replace the 20% oxidized. The starting sludge content should be 500/0.20 or 2,500 gm. This ideal state has been approached, but not attained.

The rate of oxygen utilization during assimilation is related to the mass of active sludge cells. For example, with a starting concentration of 500 mg. of cells per liter, the high oxygen demand was met in 6 hours. The peak demand occurred in 1 to 2 hours, and was about 80 μl. of oxygen per milligram of cells per hour, or about 11.4 gm. of oxygen per gram of cells. If the cell concentration was doubled, the assimilation phase was completed in about 3 hours.

XI. Storage Ability of Sludge

It has been noticed that the rates at which oxygen was used by a sludge-waste mixture differed from the rates at which purification occurred. In extensive studies on industrial wastes (Gellman and Heukelekian, 1953), acclimatized sludges showed greater rates of oxidation and purification than unacclimated normal sewage sludge. Further, the rate of purification or removal of available organic material substrate was greater than the rate of oxidation. With dairy wastes, the rate of purification was ten times the rate of oxidation, when milk solids and sludge solids were aerated in the proportion of one to one (Hoover *et al.*, 1954).

The removal of organic matter and the utilization of oxygen were followed as shown in Fig. 4. Under the conditions of the experiment, lactose (A) was removed in about 1 hour, and the remainder of the soluble organic matter (B) disappeared in another ½ hour. The oxygen utilization curve (C) showed that in 3 hours about three-eighths of the oxygen required for complete combustion was used. Since it has been shown that, for each 3 parts of C.O.D. oxidized, 5 parts are changed to cell material, we can construct curve D to represent the sum of the C.O.D. oxidized and that changed to cell material. This is done by taking the values on C and multiplying by 2.67. According to Eq. (9), D would represent the C.O.D. material removed from solution in the making of cell substance. However, the actual

[ra]te of removal of the material (purification) is much greater, and D only approaches the value of B in about 3 to 3.5 hours.

The difference between D and B must represent accumulated unoxidized C.O.D. taken up or stored by the sludge that is readily available for assimilation. The stored material requires about 3 hours for oxidative conversion before endogenous respiration predominates. Industry has taken advantage of this ability of a well-aerated sludge to rapidly purify a solution and then oxidize the stored material (Eckenfelder, 1952). Wastes from a cannery were vigorously mixed and aerated with a sludge for 20 to 30 minutes. After a short settling period, a clear effluent, low in C.O.D., was discharged. The separated sludge mass was transferred from the clarifier to a sludge stabilizer. Aeration was continued to complete the oxidation and prepare the cells for treatment of fresh incoming waste.

Studies on purification, synthesis, and storage were extended (Porges *et al.*, 1955). Purification was almost the same at 20° C. and 30° C. in that study. At 10° C., purification was still very high, and even at 2° C. as much as 50% of the C.O.D. was removed. Oxidation, however, was practically inhibited at the low temperature and was at a maximum at the highest temperature. Calculation on a C.O.D. basis showed that a well-aerated endogenous sludge is apparently able to store about half its own weight of unoxidized material. This was observed in the experiment conducted at 2° C., in which considerable waste was removed, although oxidation had practically ceased. According to these observations, a sample of cell solids removed at the peak of storage should contain about 33% of its own weight as readily oxidizable material. Actual analysis gave 26% of cell weight as

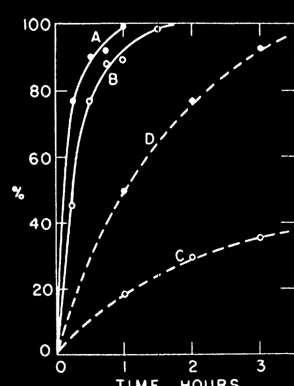

FIG. 4. Organic matter removal and oxygen utilization by aerated sludge, showing removal of lactose (A) and organic matter (B), utilization of oxygen (C), and theoretical amount of organic matter removed (D).

storage C.O.D.; the major portion, or about 19% of cell weight, was a glycogenlike substance. References have been made to glycogen content of various microorganisms (Porges *et al.*, 1955).

The hypothetical cell, $C_5H_7NO_2$, contains 12.4% nitrogen. When 1,000 mg. of these cells take up and store 620 mg. of C.O.D., disregarding new cell formation, the nitrogen content drops to about 7.5%. Oddly enough, this is about the recommended nitrogen content of sludge waste mixtures for achievement of good purification (Sawyer, 1956). A nitrogen content as low as 4% in sludge-waste mixtures may be adequate for the standard prolonged aeration periods.

Successful aerobic treatment of more concentrated industrial wastes, although simply shown in Eq. (1), is actually dependent on the many interrelated changes summarized schematically:

$$\begin{array}{ccc}
\multicolumn{3}{c}{\text{organic solubles} + \text{microorganisms} + \text{oxygen}} \\
\downarrow & \downarrow & \downarrow \\
\text{cell synthesis} & \text{storage} & \text{oxidation} \\
\text{(assimilation)} & \downarrow & \downarrow \\
\downarrow & \text{oxidation} & CO_2 + H_2O \\
\text{endogenous} & \downarrow & \\
\text{respiration} & CO_2 + H_2O & \\
\downarrow & & \\
CO_2 + H_2O + NH_3 & &
\end{array}$$

XII. Sludge Microorganisms

Inevitably, questions arise concerning the organisms that participate in the rapid aeration process of waste treatment. From the practical viewpoint, as long as treatment progresses properly, a knowledge of the type of organisms present is unnecessary. Actually those organisms grow which produce the greatest amount of cell protoplasm under the existing conditions. The sanitary engineer establishes and maintains conditions desirable for the process.

Various bacteriological studies have been made on sewage purification. Bacteria have been classified according to their physiological activity, such as proteolytic, sulfur-cycle, and nitrogen-cycle forms (Hotchkiss, 1923). An enumeration and identification of the bacterial population of a sewage treatment plant sludge showed a predominance of intestinal forms (Gaub, 1924). In activated sludge, the importance of zooglea-forming bacteria has been shown. The growth produces a slime that aids settling and purification. One species, *Zooglea ramigera*, was isolated from activated sludge (Butterfield, 1935) and extensively studied (Butterfield *et al.*, 1937; Heukelekian and Littman, 1940; Wattie, 1943), demonstrating its importance in sewage purification. Later studies showed that other organisms are also active in floc formation (McKinney and Horwood, 1952). In addition to *Zooglea ramigera*, the following were considered important: *Paracolobactrum aerogenoides, Escherichia intermedium, Nocardia actinomorpha*, and a *Flavobacterium*.

The first systematic study made on a creamery waste described 36 species, all aerobic or facultative aerobic in their oxygen requirements (Levine and Soppeland, 1926). In the absence of air, the growth of acid producers was favored, while proteolytic forms predominated in an abundance of air. A subsequent study made on a trickling filter receiving creamery wastes showed the presence of strong acid-producers or acid-destroyers, but many other forms subsisted on the end-products of lactic acid decomposition (Levine and Watkins, 1932). In a study on the microbiology and ecology of sewage filtration through sand, it was shown that the distribution of predominant species differed with the filter depth (Calaway *et al.*, 1952). The upper 12 inches had the greatest number and the widest distribution of species. Fourteen species of general heterotrophic bacteria were isolated from the various levels. Members of genera *Flavobacterium* and *Bacillus* were predominant throughout the filter and zoogleal bacteria were found in high numbers in the upper 12 inches of sand.

The organisms present during the rapid biochemical oxidation of dairy waste were isolated and studied (Jasewicz and Porges, 1956). The samples were removed from an aerator that had been in operation for 6 months. A well-aerated and agitated 18 liters of sludge-skim milk mixture was fed daily with 18 gm. of dried skim milk, after removal of the supernatant solution. Three days after the last milk addition, dilutions were plated on agar containing skim milk. All the colonies from two plates of the 10^8 dilution were isolated into nutrient broth. Each isolate was identified by morphological and physiological studies. The bacteria in this endogenous sludge numbered 32×10^8 viable organisms per milliliter. Of the 16 species found, only one grew on casein and a few on lactose. It was apparent that the isolated organisms were not those primarily responsible for the removal and oxidation of the soluble solids in milk wastes. Undoubtedly, these types of organisms were present, but were not detected at the high dilutions.

In the interval of time necessary for the identification of the organisms, the sludge-milk mixture was continually aerated and fed. Some weeks later, samples were removed for study 4 hours after a one-dose feeding of the 18 gm. of skim milk. This is the point where maximum purification occurred under the conditions imposed. In this case, there were 26×10^8 viable organisms per milliliter. The 52 isolates from two plates were classified into 15 species; the majority acted on casein, and a few produced acid from lactose. Only one, *Bacillus firmus*, utilized both casein and lactose. There was a complete change of flora from that found in the endogenous study. Table IV lists the isolates found in both stages of growth.

As may be anticipated, some of the organisms were the same as those found in the sand filters. Although a complete change of bacteria in the two phases of growth occurred, as noted in Table IV, (*Bacillus firmus* and *Bacillus lentus* were found in both stages) the results should be viewed with several reservations. An interval of several weeks separated the two studies, and, since sterile conditions were not maintained, the change may have resulted from contamination. Nevertheless, there seems to be a predominance of certain genera in specific phases of treatment.

As noted in Table V, 74% of the isolates from the assimilation phase were of the genera *Bacillus* and *Bacterium*. It may be speculated that these organisms are responsible for the high rate of purification and the ability of the sludge to remove and store oxygen-demanding substances. *Bacterium linens* alone amounted to over 40% of the total count. During the endogenous phase, 60% of all the organisms were of the *Alcaligenes* and *Flavobacterium* genera.

Protozoa are generally regarded as important members of waste disposal biota. They act as scavengers, feeding on the bacteria and helping to clar-

TABLE IV

BACTERIA ISOLATED FROM AERATED SLUDGE-SKIM MILK MIXTURE

Endogenous sludge	Assimilating sludge
Achromobacter liquefaciens	*Bacillus brevis*
Alcaligenes faecalis	*Bacillus cereus*
Alcaligenes faecalis var. *mariense*	*Bacillus firmus*
Alcaligenes viscosus var. *dissimilis*	*Bacillus laterosporus*
Bacillus circulans	*Bacillus lentus*
Bacillus firmus	*Bacillus pasteurii*
Bacillus lentus	*Bacterium healii*
Bacillus rubricus	*Bacterium linens*
Flavobacterium invisible	*Corynebacterium bovis*
Micrococcus candidus	*Flavobacterium aquatile*
Micrococcus cinnabareus	*Flavobacterium breve*
Micrococcus flavus	*Flavobacterium suaveolens*
Micrococcus pyogenes var. *albus*	*Microbacterium liquefaciens*
Micrococcus varians	*Micrococcus aurantiacus*
Pseudomonas eisenbergii	*Pseudomonas aeruginosa*
Pseudomonas oleovorans	

TABLE V

PREDOMINANT BACTERIA IN AERATED SKIM MILK SLUDGES

Genera	Endogenous (%)	Assimilative (%)
Achromobacter	2	—
Alcaligenes	26	—
Bacillus	8	31
Bacterium	—	43
Corynebacterium	—	6
Flavobacterium	34	8
Microbacterium	—	6
Micrococcus	14	2
Pseudomonas	16	4

ify the liquid. They may be used as indicators of pollution (Mohr, 1952). *Euglena, Paramecium,* and *Vorticella* are considered typical polysaprobes, but some members of these genera are mesosaprobes. Very few protozoa were found in the vigorously aerating solutions in the laboratory, but a rotifer of the genus *Lecane* was present in fair numbers, showing that the highly aerobic environment of the laboratory aerator simulated the healthy conditions of clean streams.

Although algae and diatoms were practically absent from the aeration tank, algae are of tremendous importance in stabilization ponds, where they provide oxygen for bacterial oxidation. An evaluation of literature shows a widespread distribution of stabilization ponds for sewage treatment (Fitzgerald and Rohlich, 1958; Hicks, 1958). Many species of algae are present in sewage oxidation ponds and have been described (Silva and Papenfuss, 1953), but the most numerous are *Chlorella, Scenedesmus,* and *Euglena.* The environmental conditions and nutrient requirements of the algae have been determined (Ludwig and Oswald, 1952). Under suitable conditions, oxidation or stabilization ponds are an effective and economical answer to community disposal problems.

Though fungi were practically absent in the vigorously aerating mixture of sludge and milk wastes, they are of importance in the purification of sewage by filtration. Excessive growth of the fungi present in the film decreases the efficiency of the filter by impeding percolation, and as much as 30% of the total solids of the film may be of fungal origin, interfering with aeration (Tomlinson and Hall, 1950). On the other hand, promoting the growth of fungi may enhance treatment of industrial wastes. Factors affecting the growth of some fungi associated with sewage purification have been studied (Painter, 1954). The many fungi and yeast present on trickling filters are being identified and their significance in waste treatment reappraised (Cooke and Hirsch, 1958).

XIII. Compilation of Essential Data

Various ideas, equations, and principles have been developed in the course of this presentation. Their practical application to the problem of waste treatment would be of interest. The information obtained is presented in a graphic manner in Fig. 5, which omits definite fixed units. When a known weight of sludge solids is dosed with twice its weight of available organic matter at one feeding, the sludge weight will increase about 50%, or one-half the weight of added material. After assimilation is completed, the sludge begins to digest itself, and its weight decreases. About 37.5% of the added C.O.D., or 50% of the added organic matter, disappears. The soluble C.O.D. decreases rapidly, leaving an effluent low in oxygen demand. The effluent C.O.D. may increase slightly as oxidation continues, due to dispersion of cell substances. The oxygen requirements are very high until assimilation is complete then decrease sharply during the phase of endogenous respiration of the sludge.

The tabulation shown was made from the equations and laboratory data. The figures given are based on a single-dose feeding of 1,000 gm. of ash-free skim milk powder.

It must be realized that the tabulation is calculated on the weight of available organic substance. The volume of water in which the soluble solids are dispersed or dissolved is not taken into consideration. In addi-

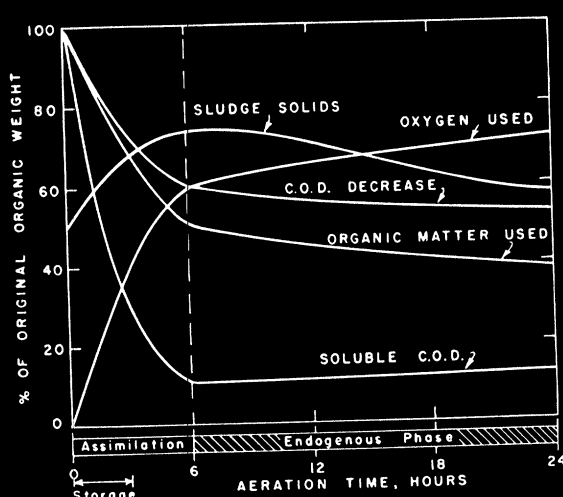

FIG. 5. Bio-oxidation of wastes (single-dose) with 50% seeding.

Skim milk organic matter	1,000 gm.
Oxygen for complete oxidation	1,208 gm.
Oxygen for assimilation (37.5% of total oxygen demand)	453 gm.
Time required for assimilation[a] (with 1,000 gm. cells)	3 hr.
Oxygen used per hour[a] (with 1,000 gm. cells)	151 gm.
New sludge organic matter produced	533 gm.
Oxygen for burn-up of new cells	755 gm.
Oxygen used for endogenous respiration varies. If rate is:	
1% per hour, then 20% per day	151 gm.
0.5% per hour, then 10% per day	76 gm.
Oxygen is required by seed sludge, also:	
1,000 gm. sludge organic matter	1,440 gm.
20% or 200 gm. per day	288 gm.
10% or 100 gm. per day	144 gm.

[a] The cell concentration determines assimilation time and oxygen needed.

tion to the strength of the waste, the rate of flow of the waste should be known. This is important in sizing a tank for the aeration treatment.

XIV. Model Calculation

The application of the data is demonstrated in the following example in which 10,000 gallons of waste are produced daily, with an average strength of 1,500 mg. per liter of C.O.D. The various values are those shown in the above tabulation but are calculated on the basis of C.O.D. instead of skim milk weight.

First, the oxygen required for total oxygen is calculated by substituting the strength and volume of the waste in the following equation:

$$\text{Pounds C.O.D.} = \frac{(\text{mg./liter C.O.D}) \times (\text{gallons of waste}) \times (\text{wt. of waste per gallon})}{1{,}000{,}000} \quad (14)$$

$$\text{Pounds C.O.D.} = \frac{1.500 \times 10{,}000 \times 8.34}{1{,}000{,}000} = 125 \text{ pounds C.O.D. per day} \quad (15)$$

If the C.O.D. is divided by 1.2, the weight of organic matter may be approximated:

$$\frac{125}{1.2} = 104.2 \text{ pounds organic matter per day} \quad (16)$$

Since assimilation requires 37.5% of the total C.O.D., then there will be needed:

$$125 \times 0.375 = 46.9 \text{ pounds of oxygen} \quad (17)$$

New sludge organic matter (ash-free) produced should be:

$$104.2 \times 53.3 = 55.5 \text{ pounds per day} \quad (18)$$

The complete oxidation of this newly formed sludge will require the remaining amount of oxygen and will be equal to the total C.O.D. from Eq. (15) less the amount used for assimilation, Eq. (17), and equals:

$$125 - 46.9 = 78.1 \text{ pounds of oxygen per day} \tag{19}$$

This approximates the amount of sludge produced, multiplied by its C.O.D., or the oxygen required for its complete oxidation:

$$55.5 \times 1.42 = 78.8 \text{ pounds oxygen} \tag{20}$$

The amount of seed sludge necessary under a given condition may be determined. The new sludge produced replaces that portion of the seed sludge oxidized. If we assume that 18% burn-up occurs during 20 hours, the 55.5 pounds of sludge produced per day should equal the 18% lost by endogenous respiration, and the starting sludge weight will be:

$$\frac{55.5}{18} \times 100 = 308.3 \text{ pounds} \tag{21}$$

One pound of well-settled sludge obtained from dairy waste occupies about 0.8 cubic foot after settling for 30 minutes. The volume will vary with the sludge characteristics and the sludge index of the particular waste being treated. For the example taken, the settled sludge will occupy:

$$308.3 \times 0.8 = 246.6 \text{ cubic feet, or } 1{,}845 \text{ gallons} \tag{22}$$

If the dairy operates 8 hours per day, the hourly oxygen requirement for assimilation becomes:

$$\frac{46.9}{8} = 5.86 \text{ pounds of oxygen per hour} \tag{23}$$

To this must be added the oxygen necessary to satisfy the endogenous respiration of the 308.3 pounds of seed or 78.1 pounds of oxygen [Eqs. (18) and (19)]. If the total aeration time is 18 hours, the endogenous requirements become

$$\frac{78.1}{18} = 4.34 \text{ pounds of oxygen per hour} \tag{24}$$

Oxygen that must be supplied each hour while the waste is added to the tank is the sum of the amounts used for assimilation and for endogenous respiration:

$$5.86 + 4.34 = 10.20 \text{ pounds of oxygen per hour} \tag{25}$$

After assimilation is completed, only 4.34 pounds of oxygen are needed per hour.

XV. Aeration Equipment

The purpose of an aeration system is to make oxygen available in the sludge-waste mixture at the rates required by the microorganisms. It will be noted that all values are given in weight units, grams or pounds. Fundamentally, volumes of air passing through a solution are of no significance. The oxygen actually dissolved and available is of importance. At sea level, a pound of oxygen is contained in about 57 to 62 cubic feet of air, depending upon humidity and temperature. At 5,000 feet above sea level, 21% more air is required to contain 1 pound of oxygen.

Oxygen availability is of prime importance, and the selection of proper aeration equipment is essential. In some cases, turbulence alone will supply sufficient dissolved oxygen. At times, oxygenation must be attained by aeration or by aeration and agitation. Once the oxygen requirements are known, desired equipment may be selected or constructed. If the oxygen demand is low, it may be satisfied by forcing air through a perforated pipe placed on the floor of the tank. This simple device, under certain conditions, allows the dissolving of 1 to 2% of the oxygen passing through the solution. The transfer efficiencies of various aeration devices were examined (Finn, 1954; Smith and Johnson, 1954; Kountz, 1956). About 5 to 10% of the oxygen may be used when air is forced through a porous plate if clogging of the pores does not occur. Impinger type aerators may give 10 to 15% transfer efficiency, while a turbine aerator will give up to 25% or more. Of significance is the oxygen adsorption rate, which gives the amount of oxygen actually dissolved per unit of time for each device at a given rate of air flow.

The aeration equipment commercially available falls into three basic types that have been described and discussed (Eckenfelder and O'Connor, 1958; Trebler and Harding, 1955). There are the diffusion units that have small orifices that include such porous media as ceramic plates and tubes and which require air flow delivered under pressure. Another type consists of mechanical aerators that entrain atmospheric oxygen by surface agitation or disperse compressed air by the shearing action of a turbine or agitator. The third type of aeration unit employs mechanical and air shear such as the impingement or jet aerator and disperses compressed or atmospheric air.

The aeration device selected to treat dairy waste in the pilot-plant study was a jet aerator, or ejector. This device is of interest because of its simplicity and absence of moving parts. The liquid forced through the ejector by means of a recirculating pump (Kountz, 1953) entraps atmospheric air via the suction connection by means of a pipe extending above the surface of the liquid. An ejector of specific type and size dissolved 1.6 pounds of oxygen in the solution per hour under established conditions. Knowing the amount of oxygen that each ejector can dissolve, the required number of ejectors for treatment can be selected. A manual describing details of theory, design, construction, and operation of dairy waste treatment by aeration has been prepared (Porges *et al.*, 1959). Under pilot-plant and industrial conditions, the selected ejector was consistently capable of adding oxygen to the solution fast enough to maintain sufficient dissolved oxygen to satisfy the bacterial demand. The use of ejectors is apparently not novel (Trebler and Harding, 1955), since they were described many years ago (Church and Hill, 1905). At least one large chemical plant is using ejector aeration for the treatment of some of its wastes (Harlow and Powers, 1947). However, the use of larger size ejectors as developed in the treatment of dairy waste is novel; these ejectors have the advantages of not clogging easily and ability to aerate great quantities of waste in a short time.

Since such a variety of many devices is in general use for the treatment of wastes, it is incumbent upon the sanitary engineer to understand the oxygen transfer characteristics of the aeration apparatus in order to avoid treatment failure by avoiding overloading and unwanted anaerobic conditions, with the associated disagreeableness.

XVI. Pilot Plant

The application of the laboratory data to pilot-plant investigations was made at the Pennsylvania State University, where a treatment plant was constructed to handle 10,000 gallons of waste daily from the university creamery (Kountz, 1953). Satisfactory operation was maintained for a number of years when 2.5-inch pipe-size ejectors were used (Penberthy,[3] model XL-96, size 7A, steam). Oxygen input could be increased about 40% by forcing air under 6 pounds pressure into the air-intake pipe.

High rates of organic material removal were attained in this simple fill-and-draw treatment system, with only slight accumulation of sludge, and no difficulty was encountered in meeting the high oxygen demand of the dairy waste. Even shock loads of whey with extremely high oxygen demand could be treated. After settling of the sludge, a clear supernatant liquid low in B.O.D. was removed, leaving a settled sludge which, after overnight aeration, served as seed for the next day. Solids removal was rapid, and a disagreeable odor was absent. Excess sludge was digested when aeration was continued at the low rate required for endogenous respiration.

XVII. Industrial Application

The application, future possibilities, development, and design of treatment plants based on the bio-oxidation abilities of living organisms for the

[3] It is not implied the U.S.D.A. recommends the above company or its product to the possible exclusion of others in the same business.

sposal of organic process wastes have been discussed by engineers (Eckenfelder and Moore, 1955). Data collected from biological treatment studies have been organized, equated, and applied (Eckenfelder and Porges, 1957). These principles are used in treating wastes from the pulp and paper, pharmaceutical, canning, citrus, dairy, and other industries. Aeration of the mixed liquor is accomplished by different types of air diffusers, but a number of dairy plants and one citrus plant treat waste using ejectors. This aeration technique is used in dairy waste units treating as little as 2,000 gallons of dairy waste batchwise and as much as 150,000 gallons or more continuously.

A schematic presentation of a batch-type treatment plant is shown in Fig. 6. Operation is simple. The waste is forced by the pump through the manifold and out through the ejectors at the bottom of the tank while air is drawn into the turbulence chambers through inlets. While the waste is received during the working day, maximum aeration is supplied. Aeration is continued for another hour, and the power is shut off. The sludge settles for 2 or 3 hours. A volume of clear effluent equal to the volume of waste received that day is then drained. Aeration is continued at the lower rate for endogenous respiration until next morning, when wastes are received again and the cycle is repeated. Calculations, used in constructing and operating a treatment plant to handle daily 25,000 gallons of dairy plant waste containing the equivalent of 300 pounds of milk solids, are available (Kountz, 1954).

A continuous process in which air is supplied under pressure to increase

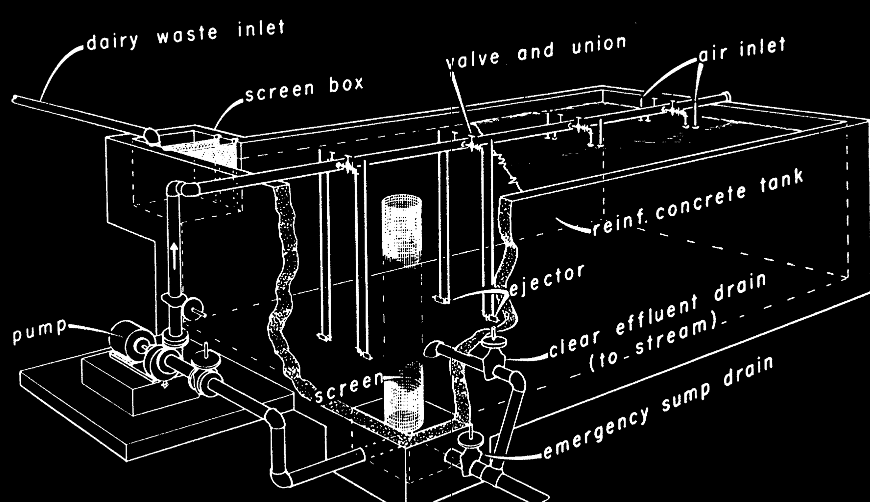

Fig. 6. Schematic presentation of a batch-type waste treatment plant.

the available oxygen is in use at another plant where 150,000 gallons of waste are treated daily. The sludge is settled in a separate chamber and returned to the main aeration chamber. There is a slight accumulation of sludge, especially in winter, but the treatment system is free of odor.

The great mass of information and experience accumulated by the fermentation industry is available for the use of sanitary engineers. Likewise, the fermentation industry may use information developed by sanitary engineers. Both groups apply the activities of microorganisms for practical purposes and have reason for more interchange of ideas. Fermentative uses of the large quantities of wastes available at some industrial plants should be investigated. Aerated sludge from an activated sewage plant contains vitamin B_{12} (Hoover *et al.*, 1951a) and could supplement animal feeds (Hoover *et al.*, 1952a). Sulfite waste liquor is used for the production of alcohol (Kure, 1956) and growth of yeast (Inskeep *et al.*, 1951). Yeasts have been grown on starch wastes (Reiser, 1954), and protein concentrate has been recovered by aerobic treatment of sulfite waste liquor (Amberg and Cormak, 1957). Conditions for the rapid growth of yeast on whey have been established (Wasserman *et al.*, 1958). In many other cases, utilization of wastes may help to pay the cost of its disposal and should warrant further investigation.

ACKNOWLEDGMENT

Laboratory investigations were carried out with the active cooperation of Miss Lenore Jasewicz, my co-worker. Pilot-plant studies were under the direction of R. R. Kountz, Professor of Sanitary Engineering, at Pennsylvania State University.

REFERENCES

Amberg, H. R., and Cormak, J. F. (1957). *Sewage and Ind. Wastes* **29,** 570–576.
Association of Official Agricultural Chemists. (1955). *In* "Official Methods of Analysis of the Association of Official Agricultural Chemists" (W. Horwitz, ed.), 8th ed., p. 29. Washington, D. C.
Burk, D., and Horner, C. K. (1939). *Wallerstein Labs. Communs.* (6) 5–23.
Butterfield, C. T. (1935). *Public Health Repts.* (*U.S.*) **50,** Reprint No. 1686.
Butterfield, C. T., Ruchhoft, C. C., and McNamee, P. D. (1937). *Public Health Repts.* (*U.S.*) **52,** 387–412; *Sewage Works J.* **9,** 173–196.
Calaway, W. T., Carroll, W. R., and Long, S. K. (1952). *Sewage and Ind. Wastes* **24,** 642–653.
Caldwell, D. H., and Langelier, W. F. (1948). *Sewage Works J.* **20,** 202–218.
Church, W. L., and Hill, G. E. (1905). U. S. Patent 762,466.
Cooke, W. B., and Hirsch, A. (1958). *Sewage and Ind. Wastes* **30,** 138–156.
Dawson, P. S. S., and Jenkins, S. H. (1949). *Sewage Works J.* **21,** 643–658.
Eckenfelder, W. W., Jr. (1952). *Proc. Ind. Waste Conf., 7th Conf.*, pp. 181–188.
Eckenfelder, W. W., Jr., and Moore, T. L. (1955). *Chem. Eng.* **62,** 189–202.
Eckenfelder, W. W., Jr., and O'Connor, D. J. (1958). "Bio-Oxidation of Organic Wastes; Theory and Design." Manhattan College, New York.

...nfelder, W. W., Jr., and Porges, N. (1957). *Appl. Microbiol.* **5,** 180–187.

...nfelder, W. W., Jr., and Weston, R. F. (1956). *In* "Biological Treatment of Sewage and Industrial Wastes" (J. McCabe and W. W. Eckenfelder, Jr., eds.), Vol. 1, pp. 18–34. Reinhold, New York.

Finn, R. K. (1954). *Bacteriol. Revs.* **18,** 254–274.

Fitzgerald, G. P., and Rohlich, G. A. (1958). *Sewage and Ind. Wastes* **30,** 1213–1224.

Fred, E. B., and Waksman, S. A. (1928). "Laboratory Manual of General Microbiology," pp. 137–138. McGraw-Hill, New York.

Gaub, W. H. (1924). *N. J. Agr. Expt. Sta. Bull. No.* **394.**

Gellman, I., and Heukelekian, H. (1953). *Sewage and Ind. Wastes* **25,** 1196–1209.

Harlow, I. F., and Powers, T. J. (1947). *Ind. Eng. Chem.* **39,** 572–577.

Helmers, E. N., Frame, J. D., Greenberg, A. E., and Sawyer, C. N. (1952). *Sewage and Ind. Wastes* **24,** 496–507.

Heukelekian, H., and Littman, M. L. (1940). *Sewage Works J.* **12,** 260–279.

Hicks, R. (1958). *N. Z. Engineering* **30,** 105–116.

Hoover, S. R., and Porges, N. (1949). *Proc. Ind. Waste Conf., 5th Conf.* pp. 137–144.

Hoover, S. R., and Porges, N. (1952). *Sewage and Ind. Wastes* **24,** 306–312.

Hoover, S. R., Jasewicz, L., and Porges, N. (1951a). *Science* **114,** 213.

Hoover, S. R., Jasewicz, L., Pepinsky, J. B., and Porges, N. (1951b). *Sewage and Ind. Wastes* **23,** 167–173.

Hoover, S. R., Jasewicz, L., Pepinsky, J. B., and Porges, N. (1952a). *Sewage and Ind. Wastes* **24,** 38–44.

Hoover, S. R., Jasewicz, L., and Porges, N. (1952b). *Sewage and Ind. Wastes* **24,** 1144–1149.

Hoover, S. R., Jasewicz, L., and Porges, N. (1953). *Sewage and Ind. Wastes* **25,** 1163–1173.

Hoover, S. R., Jasewicz, L., and Porges, N. (1954). *Proc. Ind. Waste Conf., 9th Conf.* pp. 71–79.

Hotchkiss, M. (1923). *N. J. Agr. Expt. Sta. Bull.* **390.**

Imhoff, K., and Fair, G. M. (1947). "Sewage Treatment." Wiley, New York.

Inskeep, G. C., Wiley, A. J., Holderby, J. M., and Hughes, L. P. (1951). *Ind. Eng. Chem.* **43,** 1702–1711.

Jasewicz, L., and Porges, N. (1956). *Sewage and Ind. Wastes* **28,** 1130–1136.

Kountz, R. R. (1953). *Proc. Ind. Waste Conf., 8th Conf.* pp. 382–386.

Kountz, R. R. (1954). *Food Eng.* **26,** 89–90.

Kountz, R. R. (1956). *In* "Biological Treatment of Sewage and Industrial Wastes" (J. McCabe and W. W. Eckenfelder, Jr., eds.), Vol. 1, pp. 212–214. Reinhold, New York.

Kure, A. R. (1956). *Ontario Ind. Waste Conf., 3rd Conf.* pp. 1–7.

Levine, M., and Soppeland, L. (1926). *Iowa State Coll., Agr. Expt. Sta., Offic. Publ. Bull.* **77.**

Levine, M., and Watkins, J. H. (1932). *Iowa State Coll., Agr. Expt. Sta., Offic. Publ. Bull.* **110.**

Ludwig, H. F., and Oswald, W. J. (1952). *Scientific Monthly* **74,** 3–6.

McCabe, J., and Eckenfelder, W. W., Jr., eds. (1956). "Biological Treatment of Sewage and Industrial Wastes," Vol. 1. Reinhold, New York.

McCabe, J., and Eckenfelder, W. W., Jr., eds. (1958). "Biological Treatment of Sewage and Industrial Wastes," Vol. 2. Reinhold, New York.

McKinney, R. E., and Horwood, M. P. (1952). *Sewage and Ind. Wastes* **24,** 117–123.

Mohr, J. L. (1952). *Sci. Monthly* **74,** 7–9.